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Energy-Efficient TDMA MAC Protocol for Wireless Sensor Networks Applications

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Abstract — The availability of low-powered and cheap microprocessors, radio frequency integrated circuits and the development of new wireless communication techniques, make the wireless sensor networks (WSN) one of todays most promising technologies. Minimizing energy consumption and maximizing the lifetime of the networks are key requirements in the design of sensor network applications. Optimally designed medium access control (MAC) and routing protocols minimize energy consumption and prolong the network life. In this study, we have investigated an energy-efficient adaptive TDMA (EA-TDMA) protocol for railway applications that used in communication between sensor nodes and the cluster-head (CH) placed in a railway wagon. This protocol is suitable for medium traffic applications and reduces energy consumption by shortening the idle period when devices have no data to transmit. We have developed an analytical model for EA-TDMA and compared its performance with conventional TDMA and bit-map-assisted (BMA) protocols.

Key Words – Wireless sensor networking; railway wagons; energy-efficiency; MAC protocol.

I. INTRODUCTION

Recent emergence of micro-electro-mechanical systems (MEMS) technology, wireless communications and integrated circuit design has enabled the development of low-cost, low-power, multipurpose sensor networks. This low-power sensor network can provide new monitoring and control capability in architectural infrastructure, vehicle infrastructure, including monitoring of railway signalling systems, and rail tunnel and track monitoring. Each sensor has wireless communication capability and some level of intelligence to collect data and route it to the sink node. This enhances operational efficiency. Sensor network applications require long lifetime, data accuracy, and energy efficiency. In a sensor node, power is required for data sensing, communication and data processing [1-3].

Energy efficiency is a major issue in designing an efficient WSN; the main sources of energy loss are:

- *Idle listening* occurs when a node is waiting to receive data from its neighbour nodes. A radio keeps their receiver open all the time as it does not know when a message will arrive form its neighbours. So it is seen that nodes are keeps in idle for most of the time.
- *Collision* occurs when two nodes wants to send data at the same time and interfere each other. Collision can be removed in schedule-based MAC protocols however; it is a concern issue in contention-based protocol.
- *Overhearing* takes place when a node receives packets that are destined to other nodes i.e. receiver node is not the exact destination. It is a dominant factor in high traffic load situations.
- *Over-emitting* happens when a node sends packet to its destination but its destination is not ready to receive that message.
- *Control packet overhead* is the energy required to send, receive and transmit control packet [2-3].

Optimal design of MAC and routing protocol ensures power-efficient WSN applications that minimise power consumption and hence, maximise battery lifetime of the networks. Owing to their poor energy conservation, traditional MAC and routing protocols are not suitable for WSN applications [4].

In this paper, we have investigated an energy-efficient TDMA MAC protocol using clustering techniques to monitor vertical acceleration and lateral instability of railway wagons. This protocol reduces energy dissipation in sensor nodes while transmitting information between two nodes. In this protocol each node wakes up in its allocated time slot but, turns off its radio immediately if it has no data to transmit, otherwise it transmits its data to the CH. A mathematical model has been developed to evaluate the performance of this cluster-based EA-TDMA protocol. This paper is organised as follows. Section II represents the review of existing literatures. The architecture of proposed EA-TDMA protocol is discussed in Section III. Analytical Model of EA-TDMA, TDMA and BMA protocol is discussed in Section IV. Performance evaluation of the protocol is discussed in Section V. Section VI concludes the paper with future direction.

II. LITERATURE REVIEW

An efficient use of MAC and routing protocols plays a key role in achieving energy-efficient WSN applications. The major requirements of a MAC protocol are: energy-efficiency, scalability, latency, fairness and bandwidth

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utilisation. MAC protocols generally focus on two different areas: contention based or random-access methods and schedule-based or fixed-assignment channel access methods.

Contention-based protocols are scalable and adaptable to node density or traffic load variations. However this scheme has a major limitation relating to an enormous amount of energy wasted due to collisions, overhearing and idle listening [4]. Overcoming these drawbacks are a primary concern of MAC protocol design and a few approaches that reduces these key problems have been introduced, such as S-MAC, T-MAC [4-6].

S-MAC [4] is a contention-based synchronous protocol, designed to reduce energy consumption from the sources of energy loss: *idle listening, collision, overhearing* and *control overhead.* Periodic sleep, virtual clustering and adaptive listening techniques are used in this protocol to achieve low power duty cycle that reduces energy consumption significantly. It uses virtual carrier sense techniques to reduce collision avoidance and in-channel signalling to implement overhearing avoidance. S-MAC fragments the long message into many small parts and transmits them in burst to reduce contention and communication overhead. An evaluation with the Mote developed by the UCB proved that S-MAC works 2-6 times more energy efficient than the IEEE 802.11 MAC. Simulation results show that power efficiency achieved with this protocol as it reduces collision and overhearing. As only active part of the frame is used for communication S-MAC reduces overall throughput. However, it has synchronization overhead of sending and receiving SYNC packets. It has high message latency and not suitable for a network with heavy traffic [4 - 5].

All messages are transmit in a burst of variable length in T-MAC protocol to reduce idle listening significantly. Nodes are periodically wakes up to transmit data and go to sleep again when there is no event for a specific time period. A node will be on active status until it is busy with listening and transmitting message and after waiting a period of T_A as idle it turns to sleep mode. It enhances the poor results of the S-MAC protocol under variable condition. Active period T_A is adjusted dynamically and data transmission occurs during the start of active period. Virtual clustering mechanism is used to synchronize node schedule. A back-off algorithm is used to reduce the collisions in high load and minimize latency during minimum load condition. The future-request-to-send (FRTS) mechanism is introduced to overcome early sleep problems. Determination of active period T_A is a complex work and sometime sending node may go to sleep even if the receiving node is alive. To overcome early sleeping problem FRTS and data-send (DS) packets are used which increases power dissipation [6].

Time-division multiple access (TDMA) is a scheduled-based MAC protocol in which the channel is divided into several time slots. Each node is assigned a time slot. The node wakes and transmits data only in their allocated slots and remains in sleep mode at other times [2-4, 13].

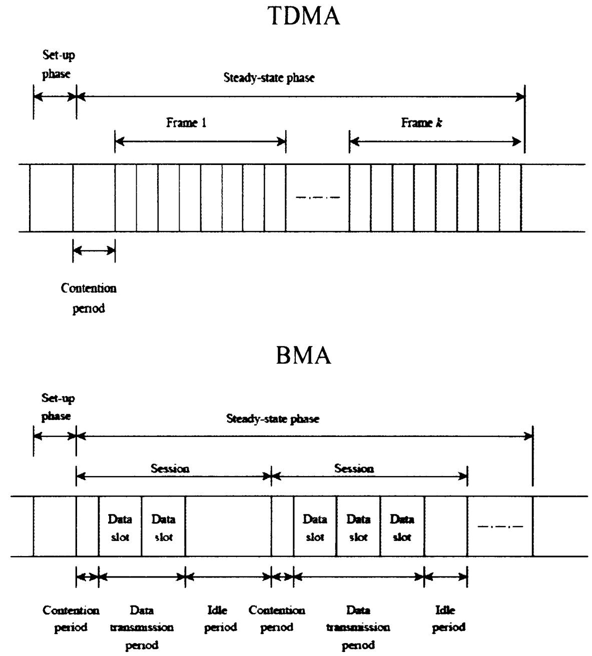

Fig. 1: Single round for TDMA and BMA protocol [8].

Conventional TDMA MAC protocols are used to prevent collisions by fixing individual time slots for each node. It also reduces energy consumption as all nodes are in sleep condition except for the transmitting nodes. Hence, TDMA protocol is a suitable choice for sensor networks. However, this protocol is suitable for a network with heavy traffic load. Usually in sensor networks there are fewer nodes in a cluster which have no data to transmit to the CH in their allocated time slots. Nodes with empty buffers still turn on their radio during their scheduled time and hence dissipate some of their remaining energy. The CH has to keep its radio on all the time in readiness to collect data from the nodes it serves. Hence, the CH does not use its energy efficiently as it wastes energy in its idle time. The energy-efficient TDMA (E-TDMA) reduces energy consumption due to idle listening. Sensor nodes keep their radios off when there is no data to transmit. However, CH has to keep on the radio during all the timeslots and hence waste energy [2-4, 8]. Fig. 1 illustrated a single round for TDMA protocol.

Low-energy adaptive clustering hierarchy (LEACH) [7] combines cluster-based routing and MAC protocol. This protocol architecture for wireless micro sensor networks achieves low energy dissipation and latency without sacrificing application-specific quality. The key design goals of LEACH are: adaptive cluster formation, energy-efficient TDMA MAC, application specific data processing. Nodes in a WSN organise themselves into local clusters with one node acting as the CH. Overall throughput of the network increases as latency is reduced and system life increases. Collision and interference are overcome by using TDMA and CDMA protocol respectively. Data aggregation mechanisms reduce the amount of data that must be transmitted to a BS, hence, reduces energy consumption. Strengths and weaknesses of highlighted MAC protocols are illustrated in Table-1.

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TABLE - I: Comparison of MAC protocols

Article	Rationale	Strengths	Weaknesses
S-MAC [4, 5]	Techniques used in S-MACs are: nodes periodically listen and sleep, virtual clustering and adaptive listening.	Synchronization overhead decreases due to adaptive listening techniques. Energy consumption reduces by sleep scheduling	As sleep, listen periods are constant, may decreases the efficiency of the protocol. Increases latency because an event may occur during sleep time.
T-MAC [6]	Introduces an adaptive duty cycle and reduces energy loss by shortening the awake period during idle condition.	It enhances the poor results of the S-MAC protocol under variable traffic load by dynamic listen period. T-MAC can change the network condition.	High latency and overhead associated with synchronization and introduces early sleeping problem.
TDMA [2, 4]	Channel is divided into several time slots and one time slots is assigned to each node. Nodes awake and transmit data in their allocated slots.	Prevent collisions by fixing individual time slots for each node and reduce energy consumption as all nodes are in sleep condition except the transmitting nodes.	There may be fewer nodes in a cluster which have no data to transmit to the CH in their allocated time slots. CH has to keep its radio on all the time.
LEACH [7]	Distributed cluster formation enables randomized, adaptive, self configuring features.	Overall throughput of the network increases as latency is reduced and system life increases. Collision and interference are overcome by using TDMA and CDMA protocol respectively.	Due to its distributed cluster formation algorithm, it cannot ensure the coverage of entire network. TDMA schedule introduces time delay.
BMA [8]	An intra-cluster communication protocol reduces energy wastes due to idle listening and collisions.	BMA has low complexity, reduces energy wastes due to idle listening and low packet latency. BMA outperforms TDMA and E-TDMA in low and medium traffic loads.	BMA is suitable only for low traffic, i.e., relatively few sensor nodes per cluster. Data may arrive in empty node at any time during node to CH data transmission.

Bit-map assisted (BMA) [8-9] is a schedule-based MAC protocol that reduces energy wastage from idle listening and collisions. The cluster setup phase is identical to LEACH [16] protocol. In BMA sensor nodes forward data to the CH only if a significant event has been observed. BMA protocol reduces energy consumption occurring in conventional TDMA systems due to idle listening in the absence of data in any node in their allocated scheduled time slots. All nodes in the cluster keep their radios on in the contention period and transmit a 1-bit control message during its allocated slot if it has data to transmit, otherwise the slot remains empty. During data transmission period, each source node turns on its radio and sends its data to the CH over its allocated slot and turns off its radio all other times. Non-source nodes keep their radios off during the data transmission period. BMA has low complexity, reduces energy wastes due to idle listening and low packet latency. BMA outperforms TDMA and E-TDMA in low and medium traffic loads. It is an energy-efficient intra-cluster low-latency protocol with low complexity and reduced energy wastes in idle listening. BMA is suitable only for low traffic, i.e., relatively few sensor nodes per cluster [8-9]. Fig. 1 represents a single round for BMA protocol.

III. ENERGY-EFFICIENT ADAPTIVE TDMA (EA-TDMA) PROTOCOL

Conventional TDMA-based MAC protocols are used to prevent collisions by fixing individual time slots for each node. This scheme also reduces energy consumption as all nodes are sleeping except the transmitting node. Nodes in the cluster send their sensed data to cluster head (CH) in their respective time slots. Nodes with empty buffers still turn on their radio during its scheduled time and the CH also keeps its radio on all the time to listen to the nodes in its cluster, this wastes energy. TDMA-performs better under high-traffic load conditions. A high traffic load means all nodes always have data to transmit. Conventional TDMA is the most suitable for an application that comprises with heavy traffic load and BMA is suitable for an application that comprises with low traffic load.

We have investigated train wagon body acceleration signals using sensor networking techniques to monitor vertical acceleration behaviour of railway wagons. In this application, accelerometer data was collected continuously from sensor nodes placed inside the wagons to investigate the train track irregularities and lateral instability. It has medium to high traffic loads. Therefore considering the application requirements, we have concentrated on developing a protocol suitable for medium to high data traffic and proposed energy-efficient EA-TDMA protocol. In the EA-TDMA protocol every node wakes up its allocated schedule but turns off its radio immediately if there are no data to transmit, otherwise it transmits its data to the CH. This protocol reduces energy consumption during data transmission by reducing idle listening period.

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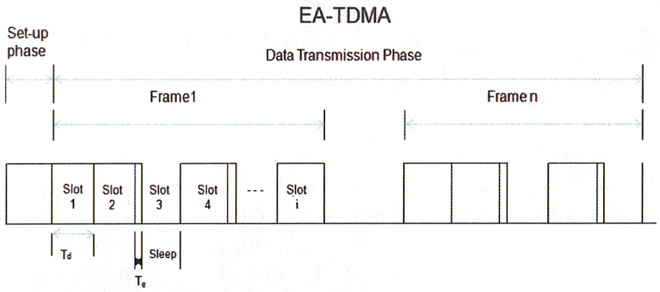

Fig. 2 Operation diagram of EA-TDMA protocol

We assume that the time slot duration in a TDMA schedule is T_d. The assigned node turns on its radio and transmits data to the CH during this period. If any node has no data to transmit it turns off its radio immediately. Therefore, we assume that the radio is turned off after time T_e, instead of remaining on for the entire time period of duration T_d, as illustrated in Fig 2.

To meet the requirements of WSNs, some assumptions of this approach are: nodes are static throughout the network; energy levels of the normal nodes are almost identical but die at almost the same time; CH has higher energy level than normal nodes; and all data slots in a TDMA schedule are the same size. We have divided the operation of the proposed protocol into rounds. Each round comprises of a set-up and a data transmission phase. Both cluster formation and CH selection occur in the setup phase, while data transmission from node to the CH and on to the BS occurs during data transmission phase, as described in the following details.

Setup Phase: Considering application area and simplicity in this study we assume the network consists of a multiple fixed cluster in which there is one CH is located in the centre of the cluster. Based on application and cluster size we have considered direct transmission for data communication between source nodes to CH instead of multihop data transmission. In setup phase, the CH builds a TDMA schedule and broadcasts the schedule to all nodes within the cluster. CH also informs all nodes about the start of current round, frame start/stop time, number of frame in a round.

Data Transmission Phase: The data transmission phase contains l frames. The size and duration of each of the frames are fixed. Nodes send their data to the CH once per frame during their allocated time slots. We assume that there is one CH node and N non-CH nodes in a cluster. During the data transmission period each node turns on its radio in its assigned time-slots and transmits data to the CH. If any node, after turning on its radio finds an empty buffer, i.e., there is no data to transmit, then the node turns off its radio immediately to save energy. The nodes turn into sleep mode instead of idle mode in the absence of data. Non-CH nodes transmit sensed data to the CH's buffer. After receiving all data from the nodes, the CH aggregates the data.

After a predefined time, the system begins the next round and the whole process is repeated. A timing diagram of the proposed EA-TDMA protocol is illustrated in Fig. 3.

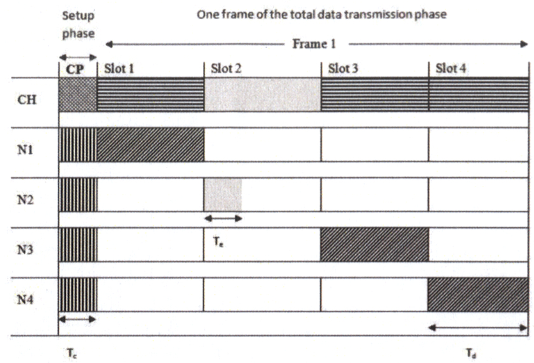

Fig. 3: Timing diagram of EA-TDMA protocol

IV. Analytical Model of EA-TDMA Protocol

We analyse our proposed protocol in a cluster-based network in which there are one CH and N non-CH nodes. Assuming that there are l frames in a round and n_k source nodes in the k_{th} frame. The nodes which have data to transmit are called source nodes. Bernoulli Trail, as used in BMA [9] protocol has been used to calculate the probability that a node has data to transmit. Hence, n_k is a Binomial random variable and source node in a frame would be $E[n_k] = Np = n,\ k = 1, 2,..,l$ where p = probability. The number of source nodes has varied from frame to frame. The power consumption in the transmit mode and the receive mode are respectively P_t and P_r. The typical power consumption in the proposed protocol occurred during turn on and empty checking period of the idle nodes: P_e. For simplicity, as stated in [4, 7], the energy required to turn on the radio by the source nodes for transmission or reception is negligible, hence ignored in the analysis here. T_d is the time required to transmit or receive a data packet, and T_c is the time required to transmit/receive a control packet. The time required for a node to switch on, check its buffer and turn off its radio is T_e. Power consumption and energy dissipation of an idle node is P_i and E_{in} respectively. The time required for the cluster-head to transmit a control packet for BMA is T_{ch}.

Initially, an analytical model was developed based on the energy model [9] for the EA-TDMA and then compared with the conventional TDMA and BMA protocol.

A. EA-TDMA Protocol: During setup phase, CH and all nodes keep their radios on and communication takes place between the CH and other nodes. In this period, the CH selects time slots for individual nodes for data communication and informs all nodes in the cluster. Therefore, energy consumption by CH to send a control packet is $E_{ch} = P_tT_c$ and energy consumption by each node to receive control packet is $E_n = P_rT_c$. Total energy consumption during setup phase for all nodes is: $E_C = P_tT_c + N P_rT_c$

Each node transmits a maximum of one packet per frame interval. During a frame, transmission energy dissipated in a data node is $E_{dn} = P_tT_d$. Energy dissipated in a node that has

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no data to transmit to the CH is $E_e = P_e T_e$. The energy E_e is used to switch on, check transmit buffers and then turn off the radio module. The energy consumed by the CH is $E_{ch\text{-}e} = n\, P_r T_d + (N - n)\, P_i T_d$. Therefore, the system energy dissipation in the k_{th} frame is:

$$E_{Se} = n\, P_t T_d + (N - n) P_e T_e + (N - n)\, P_i T_d + n\, P_r T_d \qquad (1)$$

Assume, there are l frames in a round. Therefore energy consumption of the system in a round, of the proposed protocol is:

$$E_{EA\text{-}TDMA} = P_t T_c + N\, P_r T_c + l[n\, P_t T_d + (N - n) P_e\, T_e + (N - n)\, P_i T_d + n\, P_r T_d\,] \qquad (2)$$

B. TDMA Protocol: During the k_{th} frame, the energy dissipation in a source node is $E_{dn} = P_t T_d$. A non-source node, i.e., the empty-buffer node turns on its radio and keeps idle during its scheduled time slots consuming energy $E_{in} = P_i T_d$. Energy consumption in the CH is $E_{ch} = n\, P_r T_d + (N - n)\, P_i T_d$

Energy consumption during setup phase of TDMA is the same as EA-TDMA. Therefore, the average energy dissipation in a round is

$$E_{TDMA} = P_t T_c + N\, P_r T_c + l[n\, P_t T_d + 2(N - n) P_i\, T_d + n\, P_r T_d\,] \qquad (3)$$

C. BMA Protocol: In BMA there is a contention period in each session when all nodes keep their radios on. Each source node transmits a control packet during its scheduled slot and remains idle *(N-1)* slots. Total energy consumption by each source node during a single session is $E_{dn} = P_t T_c + (N\text{-}1)\, P_i T_c + P_r T_{ch} + P_t T_d$. Each non source node stays idle during the contention period and keeps its radio off during the data transmission periods and hence energy consumption is $E_{in} = N\, P_i T_c + P_r T_{ch}$. During the contention period the CH node receives n control packets and stays idle for *(N-n)* slots. Energy dissipation by the CH is $E_{ch} = n\,(P_r T_c + P_r T_d\,) + (N\text{-}n)\, P_i T_c + P_t T_{ch}$

The average system energy dissipation in each round in BMA protocol is:

$$E_{BMA} = l[n(P_t T_c + (N\text{-}1)\, P_i T_c + P_r T_{ch} + P_t T_d) + (N\text{-}n)(\, N\, P_i T_c + P_r T_{ch}) + n\,(P_r T_c + P_r T_d\,) + (N\text{-}n)\, P_i T_c + P_t T_{ch} \qquad (4)$$

V. RESULTS AND ANALYSIS

We compare EA-TDMA protocol with the BMA and conventional TDMA protocol in terms of energy dissipation. For analytical analyses we have used Rockwell's [10] WINS model as used in the BMA protocol. In this model the radio transceiver uses 462 mW for transmitting, 346 mW for receiving and 330 mW for idle listening. The data rate is 24 kbps. Assume a data packet size of 250 bytes and a control packet size of 18 bytes. In this experiment we assume $P_i = P_e$. We compare the above three protocol in terms of energy dissipation.

Fig. 4 is drawn by noting the above conditions that provide comparison of the EA-TDMA, TDMA and BMA protocols as a function of probability p. In this case $N = 10$ and there are $l = 2$ frames in a round. It is observed that for very low traffic when p= 0.1 to 0.2 the BMA protocol is superior to that of the EA-TDMA and TDMA protocols. However, energy consumption of BMA increases linearly when $p \geq 0.3$ and EA-TDMA protocol outperforms both BMA and TDMA protocols. EA-TDMA protocol outperforms TDMA protocol except for heavy traffic. For heavy traffic energy dissipation of EA-TDMA and TDMA are same which is much less than the BMA protocol. Therefore, we may conclude that the EA-TDMA protocol is most suitable for medium traffic load.

Fig. 5 compares MAC schemes in terms of energy, where nodes N are variables and frame $l = 10$ and probability $p = 0.6$. EA-TDMA protocol outperforms both BMA and TDMA protocols in terms of energy consumption. EA-TDMA protocol saves more energy if the number of nodes increases in the network. Hence, EA-TDMA is suitable for large networks.

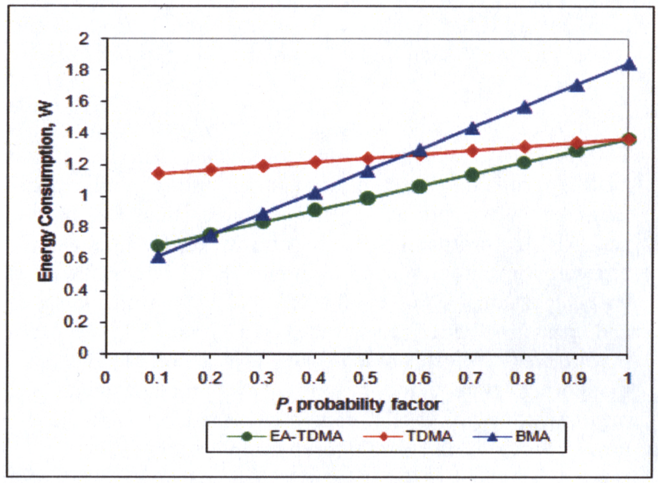

Fig. 4: Comparing the energy dissipation of EA-TDMA protocol with BMA and conventional TDMA protocol as a function of probability p.

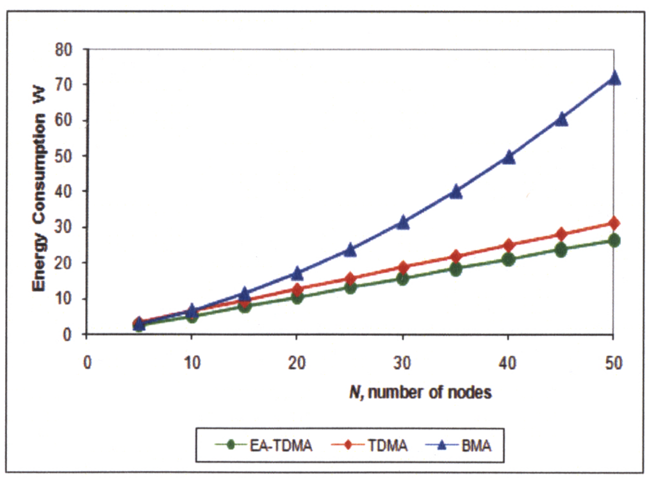

Fig. 5: Energy dissipation of EA-TDMA, BMA and TDMA protocols as a function of number of nodes in a cluster, N.

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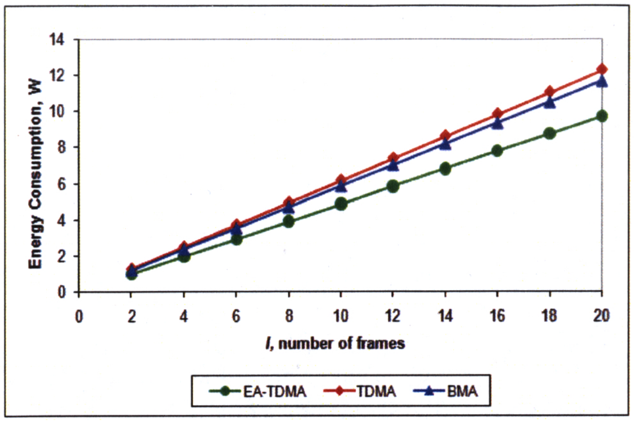

Fig. 6: Comparing the energy dissipation of EA-TDMA with BMA and TDMA protocol as a function of number of frame, *l*

From Fig. 6, it is observed that EA-TDMA protocol saves more energy if the number of frames per round increases and outperforms BMA and TDMA protocol in terms of energy dissipation.

From the above analytical results we may conclude that EA-TDMA protocol is more energy-efficient than BMA and TDMA protocols in case of medium traffic applications. However, BMA protocol performs better than EA-TDMA and TDMA protocols in case of low traffic applications especially event driven applications. For high traffic load energy consumption of EA-TDMA and TDMA are the same and perform better than the BMA protocol. We have investigated a cluster-based TDMA protocol to develop a monitoring system for railway. This problem demanded medium to high traffic conditions, therefore EA-TDMA protocol is the most suitable for this application.

VI. Conclusion

In this study, considering traffic load of the application, a cluster-based energy-efficient adaptive TDMA-based MAC protocol has been investigated for railway to monitor typical dynamic behaviour of railway wagons. A mathematical model has developed for the proposed EA-TDMA protocol and compares its performance with conventional TDMA and BMA protocols.

Analytical results prove that EA-TDMA protocol outperforms both TDMA and BMA protocols for medium to high traffic. From experimental results it has observed that BMA protocol is superior to EA-TDMA especially for low traffic or event driven applications. However, if the probability $p \geq 0.3$, EA-TDMA performs better than BMA protocol which is natural scenario for our railway applications.

This study is still on introductory stage and needs to be developed in different areas. Therefore, it deserves further investigation that focuses on some specific areas such as:

- investigate energy-efficient routing protocols and their integration with the proposed EA-TDMA algorithm.
- validate the analytical results stated in this paper using simulation software.
- reduce power consumption of the protocol by introducing duty cycle in CH.
- increase CHs lifetime by introducing rotational CH in the cluster.
- integrate the protocol with machine learning algorithm to develop monitoring signal.

References

[1] G. M. Shafiullah, A. Gyasi-Agyei, and P. Wolfs, "Survey of wireless communications applications in the railway industry," in *Conf. on Wireless Broadband and Ultra Wideband Comm.*, Sydney, Aug'07.

[2] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam and E. Cayirci, "A survey of Sensor Networks." *IEEE Communications Magazine*, vol. 40, August, 2002, pp.102-114

[3] D. S. Sokwoo Rhee and S. Liu, "Techniques for minimizing power consumption in low data-rate wireless sensor networks." *Wireless Communications and Networking Conference*, vol. 3, March 2004, pp. 1727-1731.

[4] Wei Ye, John Heidemann, and Deborah Estrin, "An energy-efficient MAC protocol for wireless sensor networks," in Proceedings of the IEEE Infocom, pp. 1567-1576. New York, NY, USA, USC/Information Sciences Institute, IEEE. June, 2002

[5] Wei Ye, John Heidemann, and Deborah Estrin, "Medium Access control with coordinated adaptive sleeping for wireless sensor networks," IEEE/ACM trans. on Networking, vol. 12, pp. 493-506, Jun'04.

[6] K. L. Tijs Van Dam, "An adaptive energy-efficient MAC protocol for Wireless Sensor Networks," in SenSys'03, Nov'03, pp. 171 - 180.

[7] W.R. Heinzelman, A.P. Chandrakasan, and H. Balakrishnan, "An application-specific protocol architecture for wireless microsensor networks," *IEEE on Wireless Communications Trans.*, vol.1, No.4, Oct'02, pp. 660-670.

[8] Jing Li, "A bit-map assisted energy-efficient MAC scheme for wireless sensor networks," Master's thesis, Electrical Engineering, Mississippi State University, May 2004.

[9] Jing Li, and Georgios Y. Lazarou, " A bit-map-assisted energy-efficient MAC scheme for Wireless Sensor Networks", in *Proceedings of 3rd International Symposium on Information Processing in Sensor Networks (IPSN '04)*, pp. 55–60, Berkeley, Calif, USA, April 2004.

[10] V. Raghunathan, C. Schurgers, S.Park, and M.B. Srivastava, "Energy-aware Wireless Microsensor Networks," *IEEE signal Processing Magazine*, Mar'02, pp.40-50.

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